Probing the diffuse ISM with carbon radio recombination lines using NenuFAR

Bright radio sources: Cassiopeia A, Cygnus A, Taurus A

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Outline

- Introduction: Generalities on RRLs in the diffuse ISM
- Cassiopeia A and Cygnus A
- Taurus A
- Perspectives

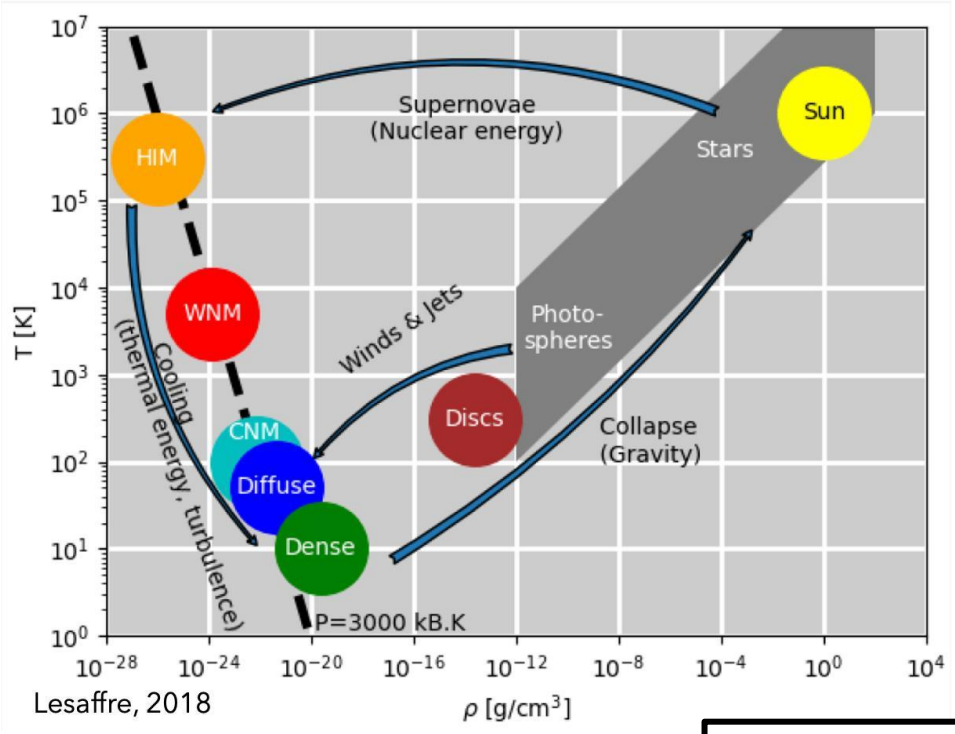
Introduction

Where does Carbon recombination occur ?

What can CRRLs tell us about the diffuse ISM ?

- The cycle of matter in the ISM
- Phase transition
- Line profiles
- The NenuFAR interferometer

The cycle of matter in the ISM



Lesaffre, 2018

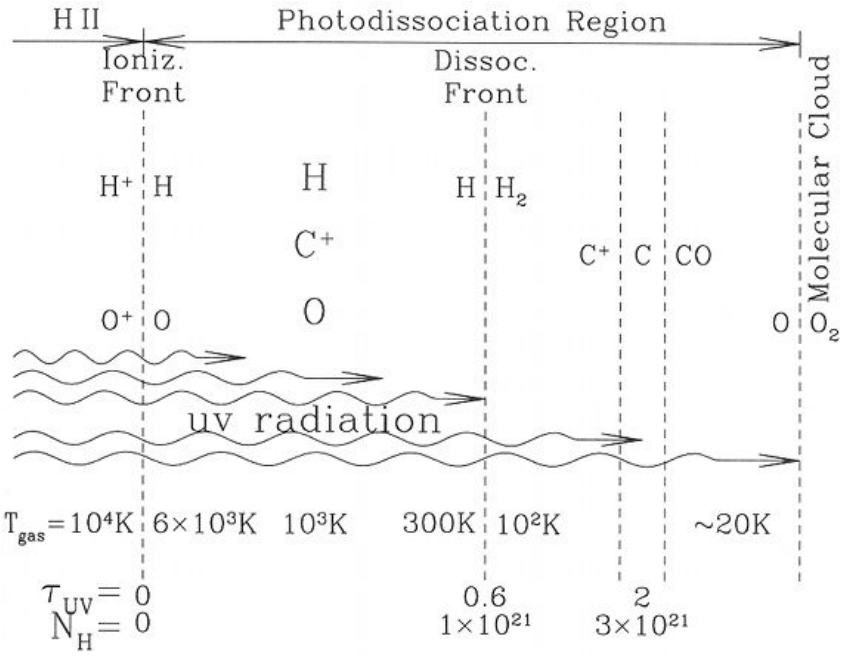
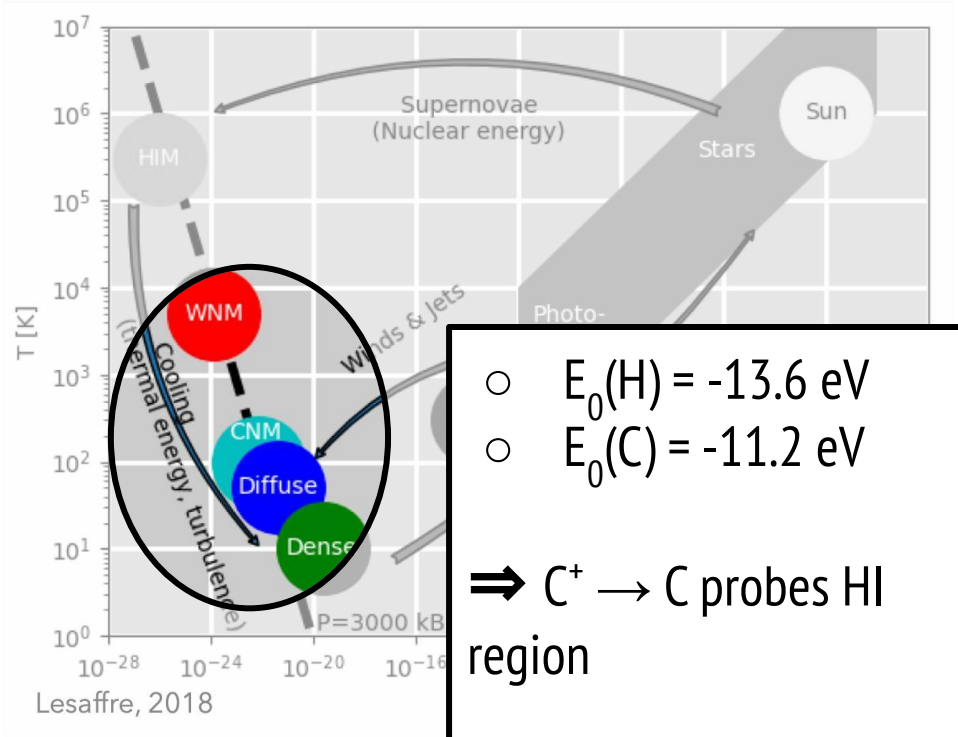


Figure 31.2 Structure of a PDR at the interface between an H II region and a dense molecular cloud.

What drives the transition between different ISM phases ?

Carbon recombination



- $E_0(H) = -13.6$ eV
- $E_0(C) = -11.2$ eV

⇒ $C^+ \longrightarrow$ C probes HI region

In which phase ?

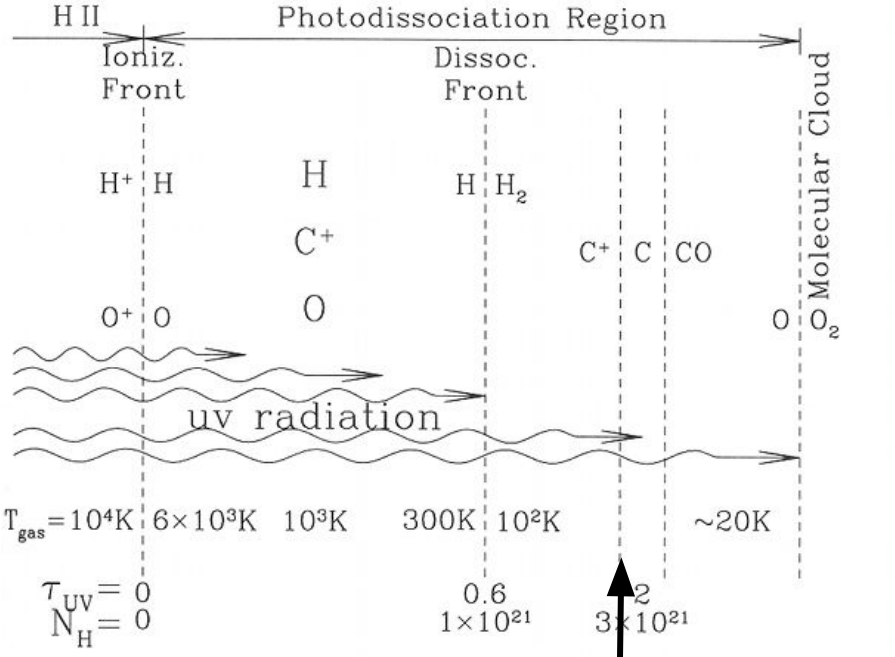
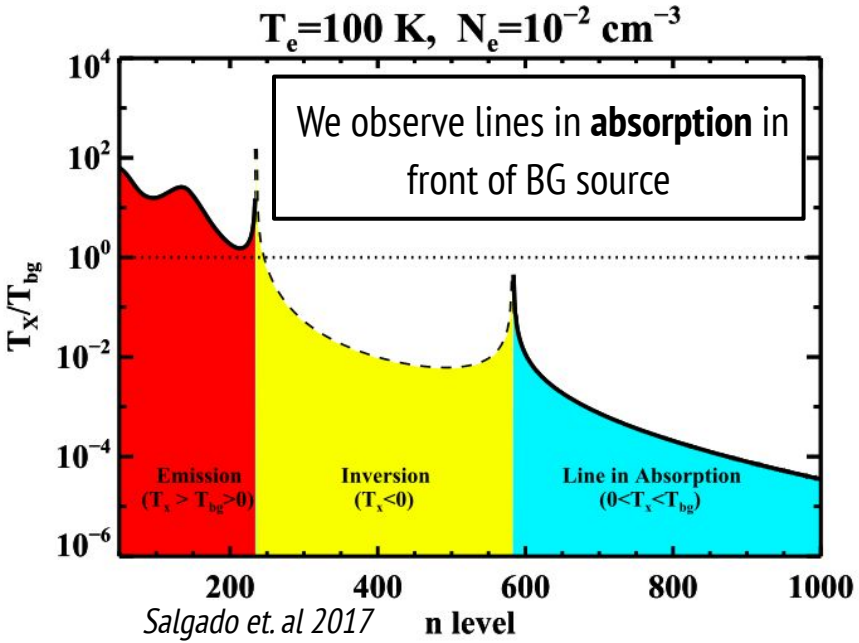


Figure 31.2 Structure of a PDR at the interface between an H II region and a dense molecular cloud.

Carbon Ionization front

CRRLs specificities at low frequencies (~50 MHz)

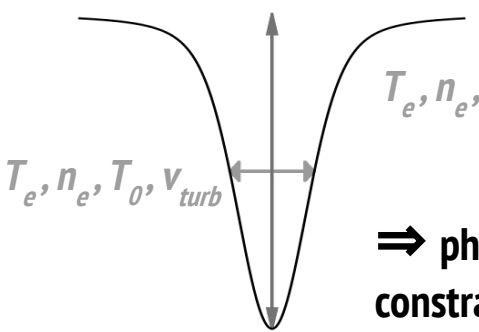


Salgado et. al 2017

Cnα transitions for n ∈ [400,850] (i.e [10,85] MHz):

$\nu_{n+1\rightarrow n} \propto [n^{-2} - (n+1)^{-2}] \simeq 2\, n^{-3}$

⇒ **450 lines in 70 MHz**



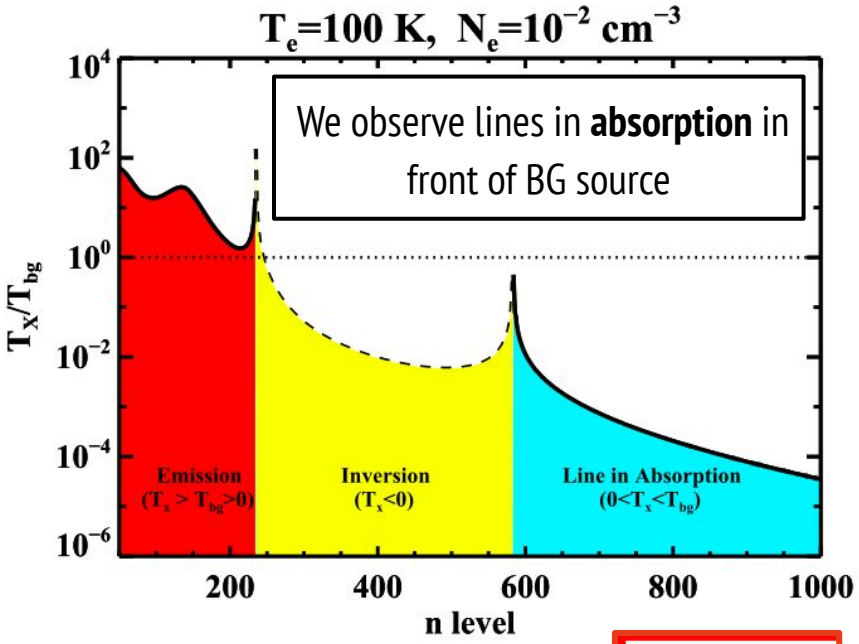
Gordon & Sorochenko, 2009

⇒ **physical/chemical constraints on the local ISM**

Indicative of the type of phase

$$T_e,\ n_e,\ v_{turb},\ T_0,\ L$$

CRRLs specificities at low frequencies (~50 MHz)



We observe lines in **absorption** in front of BG source

Salgado et. al 2017

$T_e,\ n_e$

Cnα transitions for n ∈ [400,850] (i.e [10,85] MHz):

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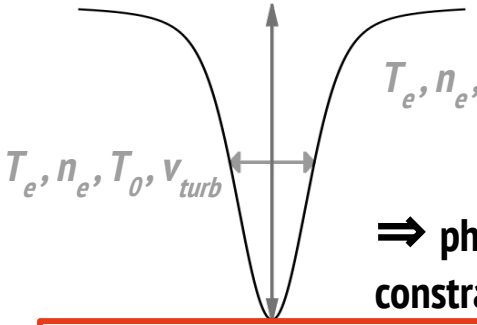
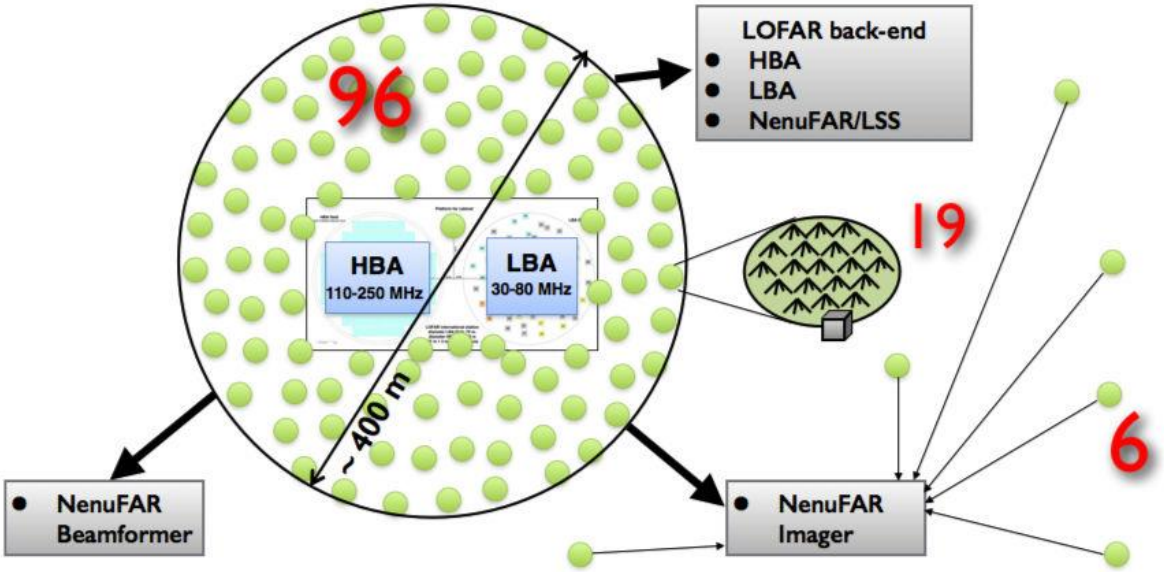


⇒ **physical/chemical constraints on the local ISM**

Key to understanding how diffuse ISM condenses into dense clouds

NenuFAR (**N**ew **e**xtension in **N**ançay **u**pgrading LO**FAR**)

Standalone radiotelescope + LOFAR extension + SKA pathfinder



NenuFAR website

EXPERIMENTAL SETUP

- ~80 mini-array of 19 antennas

- **Beamforming mode**
- Frequency range : **[10, 85] MHz**
- spectral resolution **df ~ 95 Hz**
- angular resolution ~ 1°
- temporal resolution ~ 5ns, rebinned at 30s
- 2 hours observation sessions

- LT10 : Radio Recombination Lines

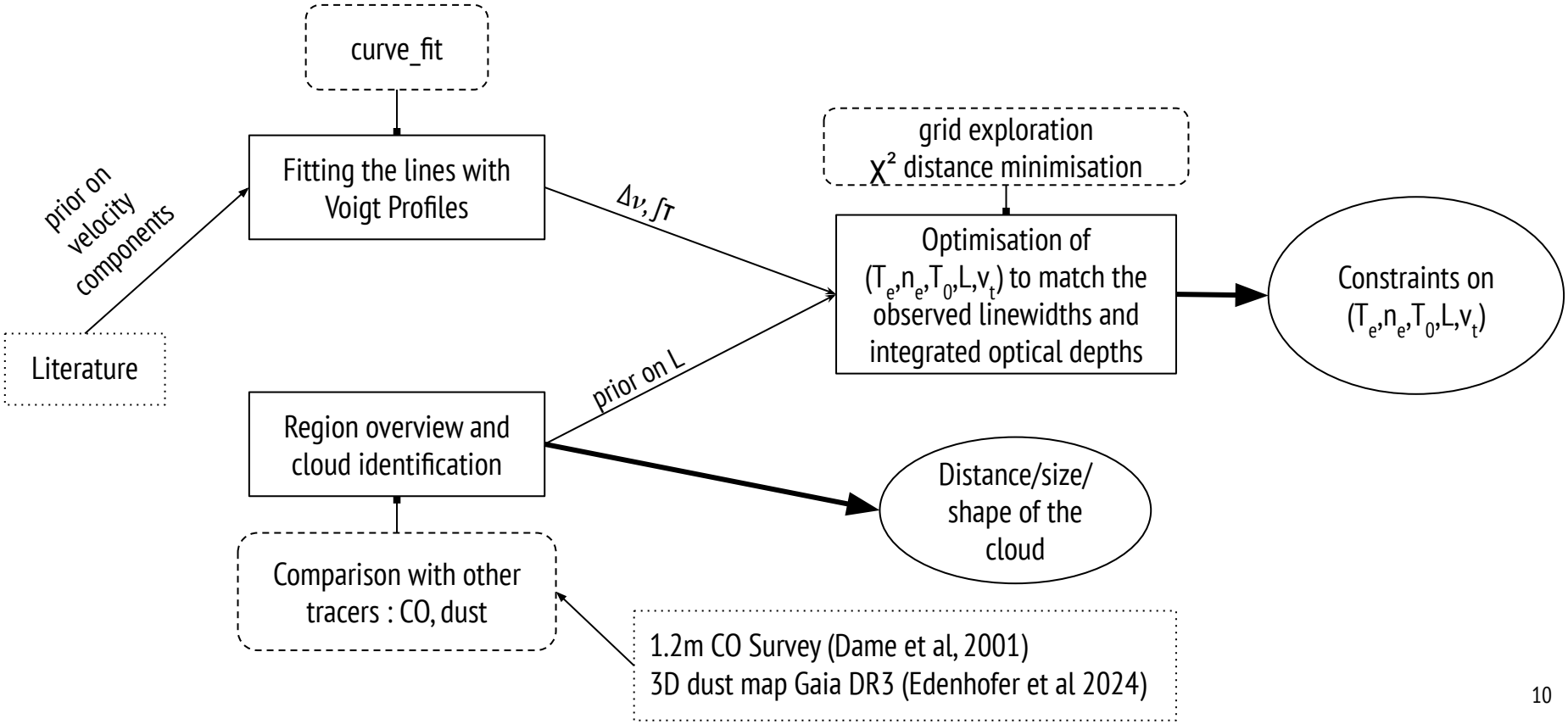
➢ Key Project since 2019, when NenuFAR was 1st commissionned

Cassiopeia A
Cygnus A

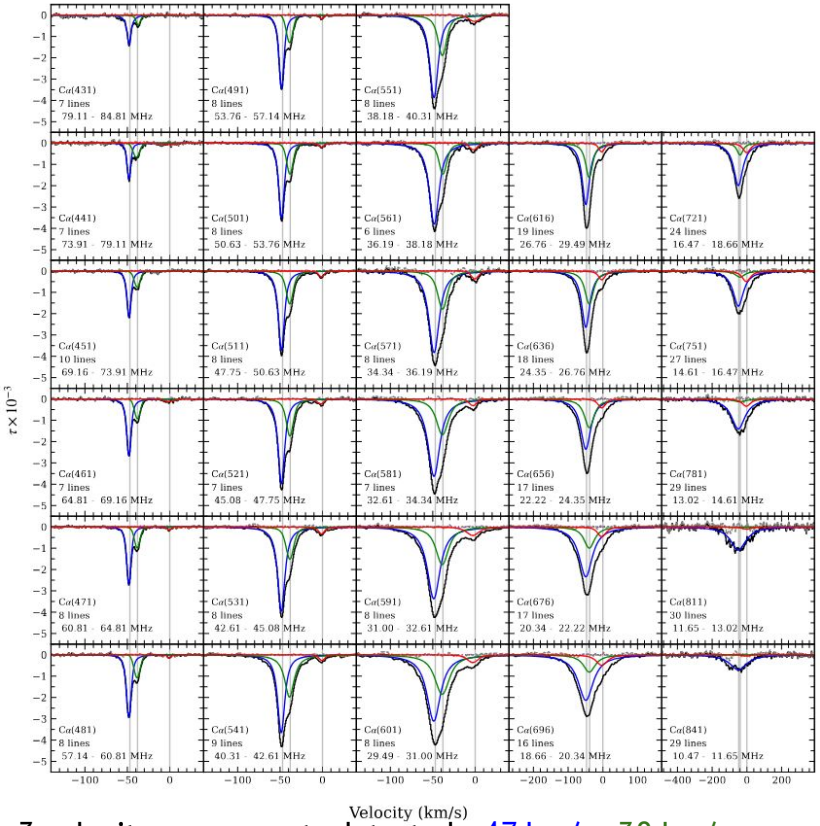
Comparison to LOFAR results

- (Data processing pipeline)
- Data analysis methodology
  - Line fitting
  - Cloud identification
  - Optimisation of the physical parameters
- Results

Data analysis methodology



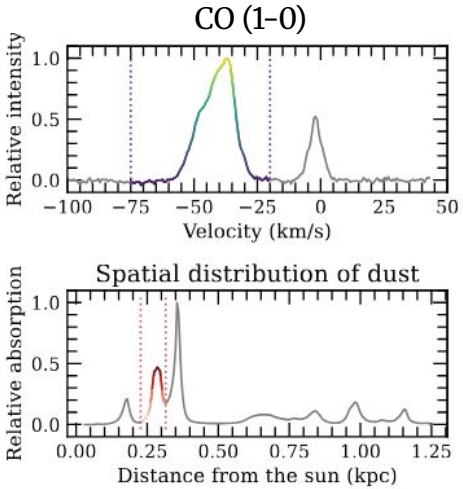
Line fitting

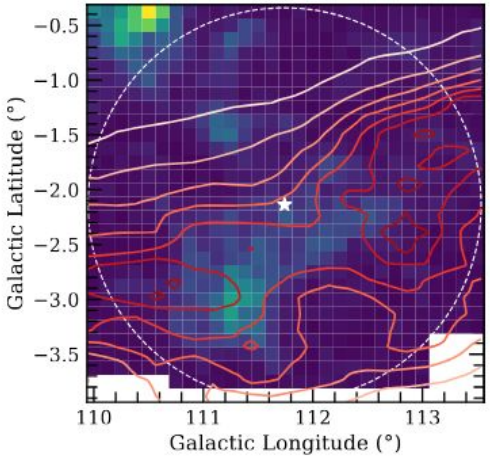


3 velocity components detected: -47 km/s, -38 km/s and 0 km/s

Cloud identification

Example: -47 km/s component of Cas A

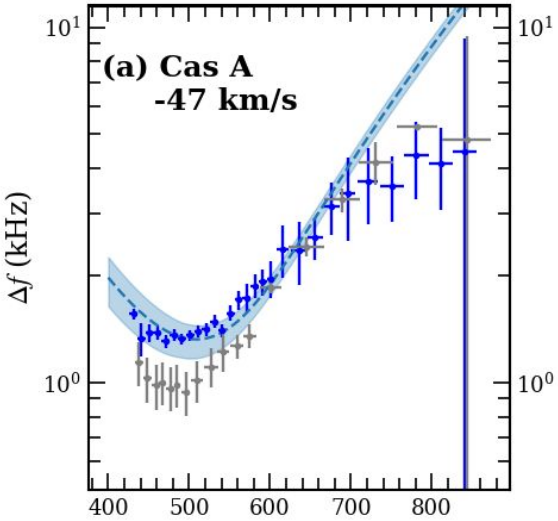


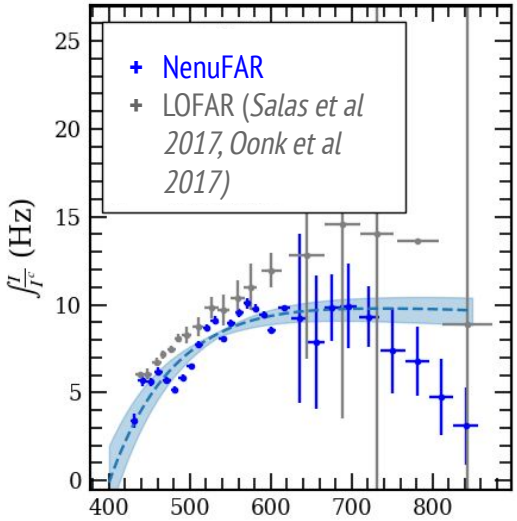


Overplot of CO (Dame et al. 2001) and dust map (Edenhofer et al. 2024)

Cros et al, 2025

Constraints on the physical parameters

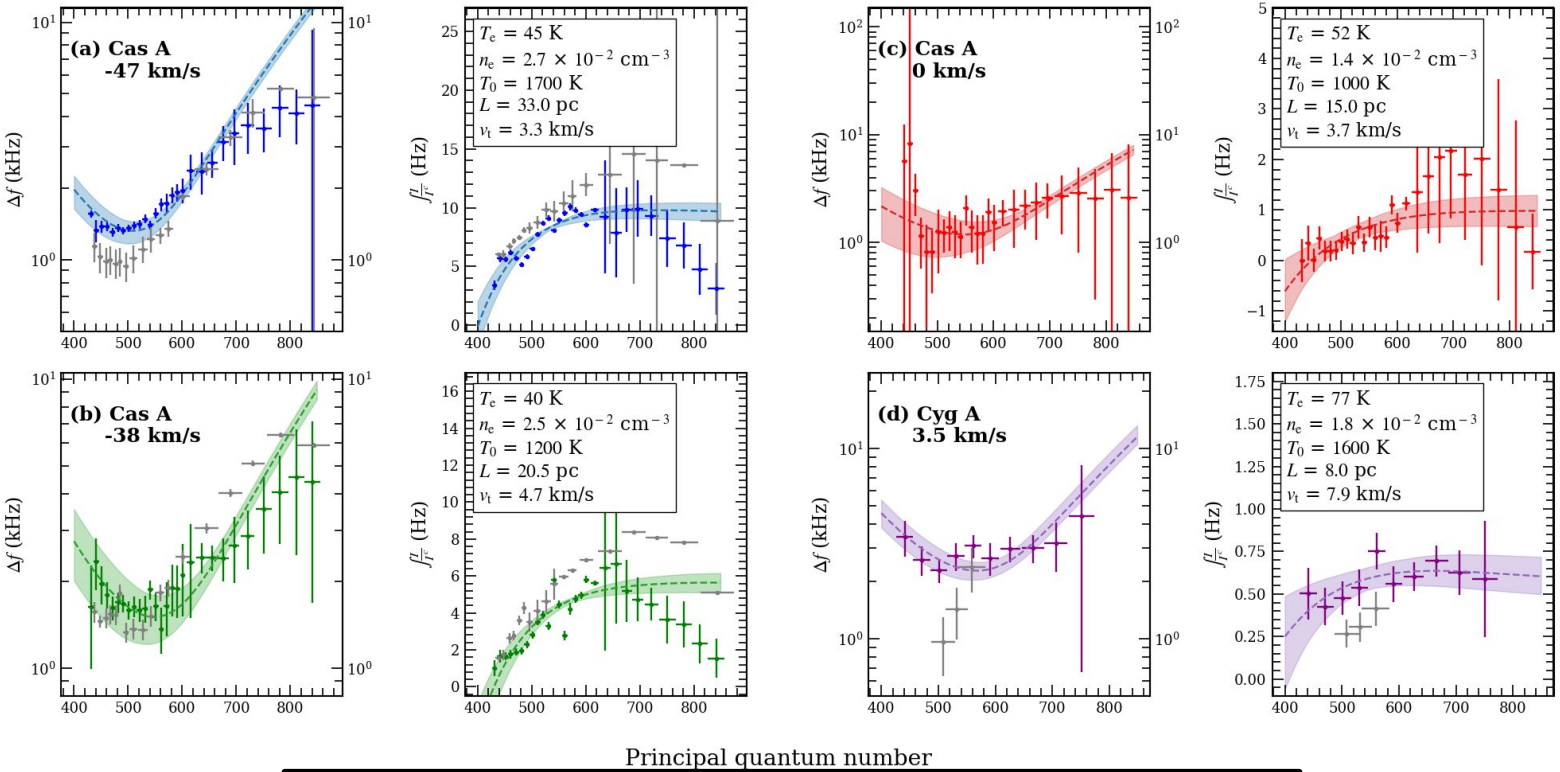




	LOFAR	NenuFAR
T_e	60 – 98 K	35 – 50 K
n_e	2 – 3.5 $\times 10^{-2}$ cm^{-3}	2.7 – 3.9 $\times 10^{-2}$ cm^{-3}
T_0	1250 – 1650 K	1700 +/- 100 K
v_t	2.0 km/s	2.7 – 3.8 km/s
L	34.1 – 36.5 pc	33 +/- 0.5 pc

General agreement with LOFAR results

Results for every detected clouds



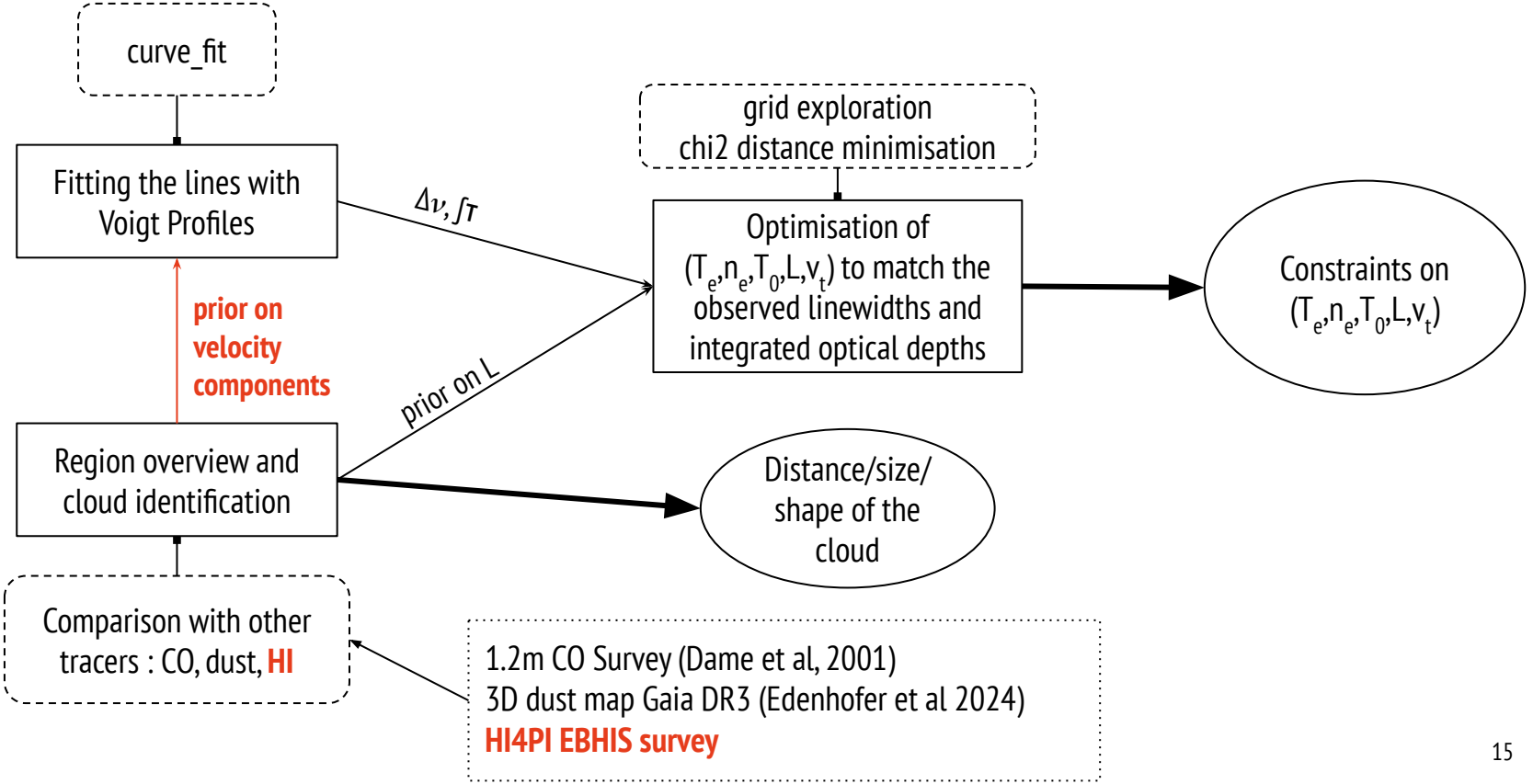
The physical parameters inferred suggest CNM phases

Taurus A

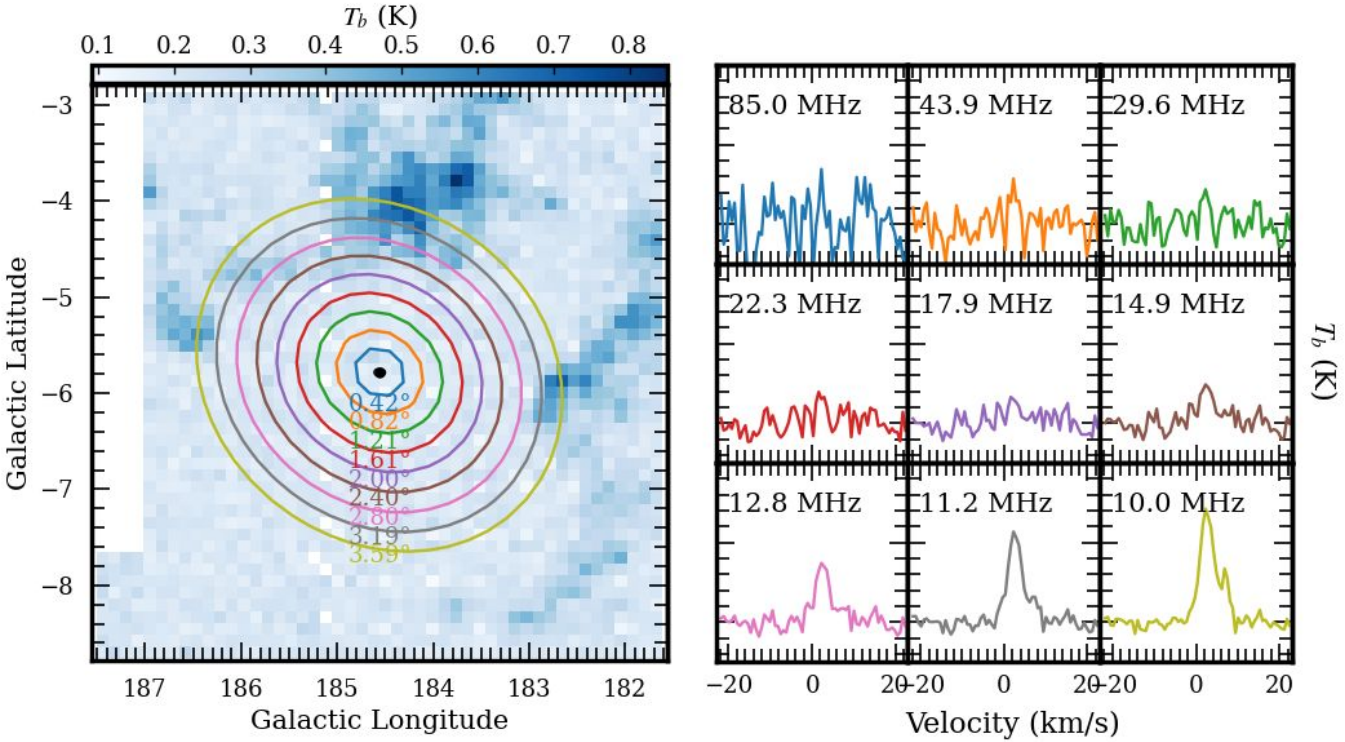
New source: no prior information regarding CRRLs

- Adaptation of the analysis methodology
- Overview of the observed region
  - CO
  - HI
- CRRLs

Data analysis methodology



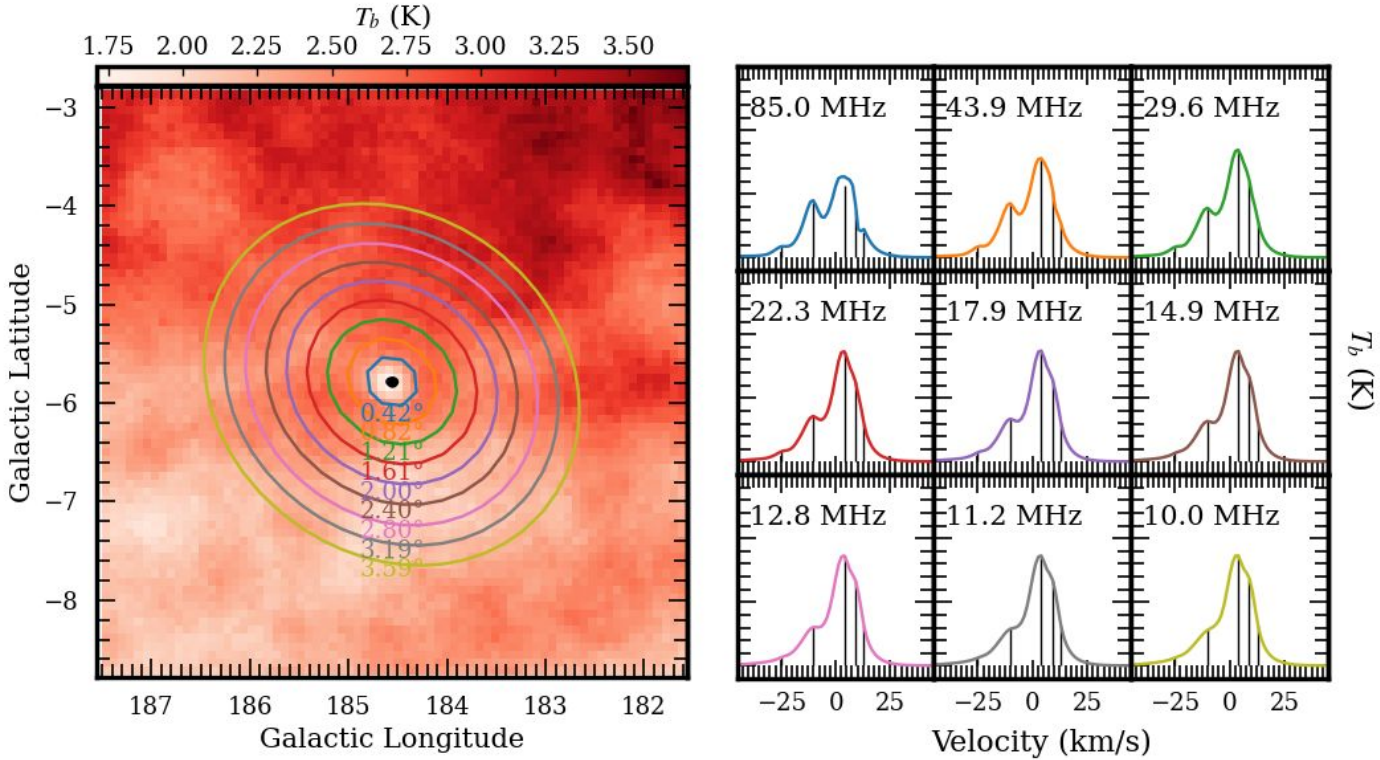
Taurus A - CO map, 1.2m CO survey



2 velocity components:

- 3 km/s
- 7 km/s

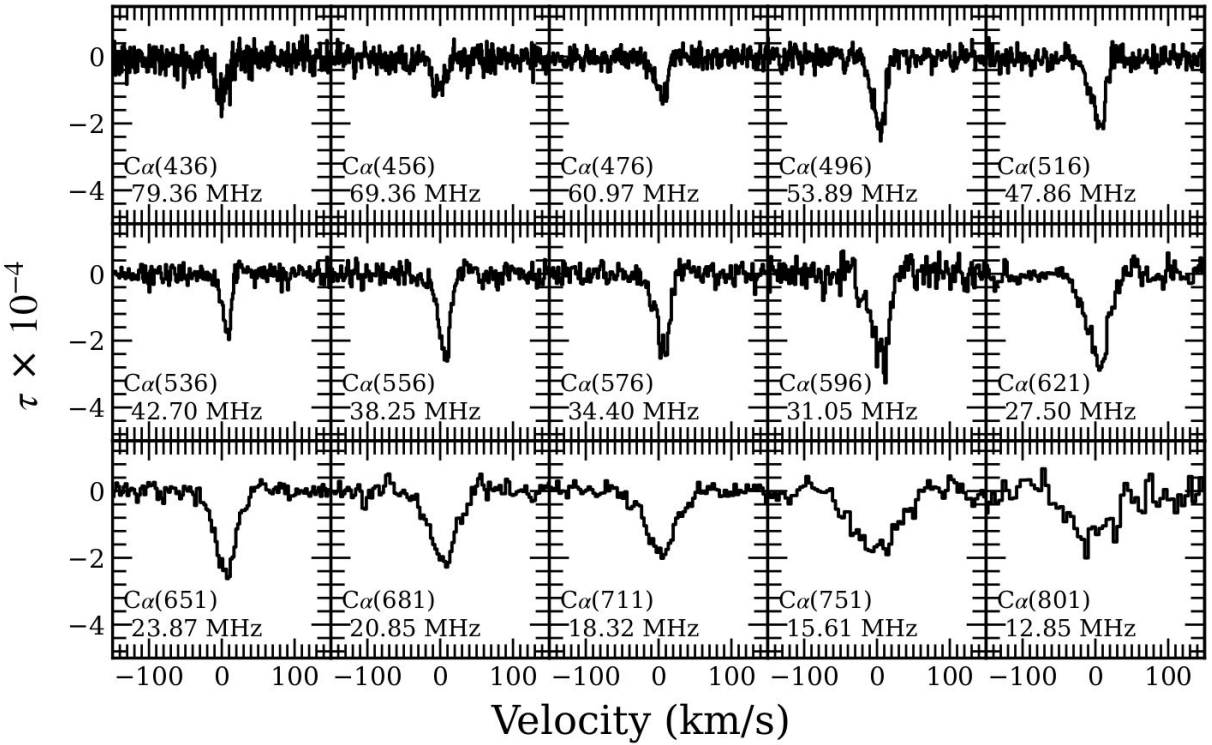
Taurus A - HI map, HI4PI EBHIS survey



5 velocity components:

- -25 km/s
- -10 km/s
- 3 km/s
- 7 km/s
- 13 km/s

CRRLs: component determination



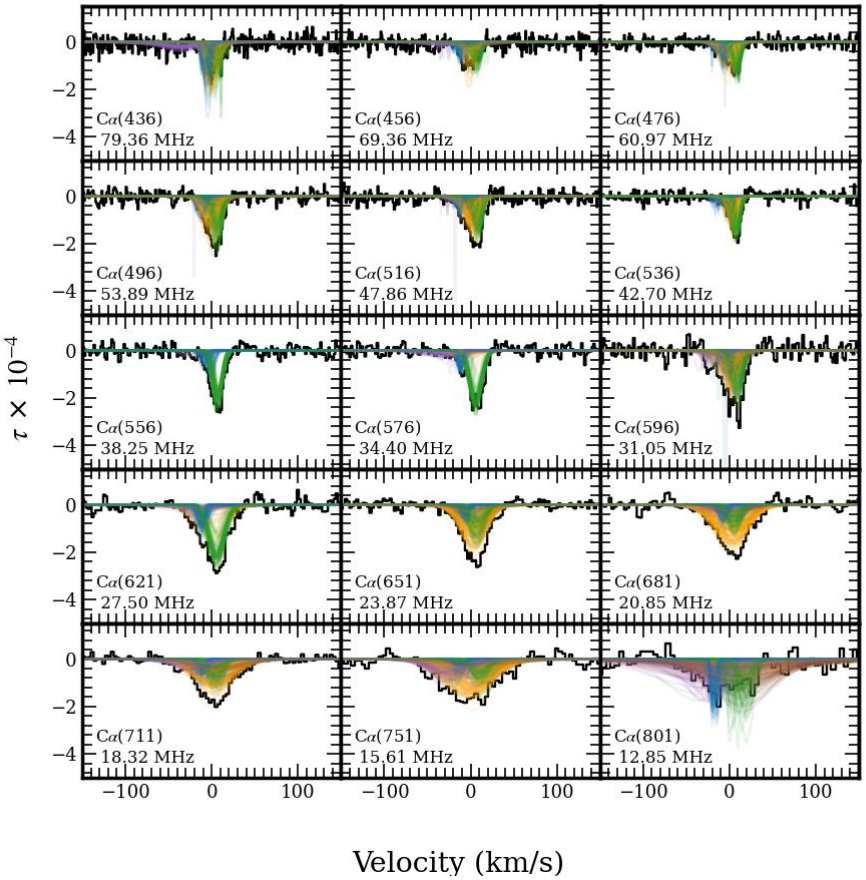
How many velocity components are present in the CRRLs spectra ?

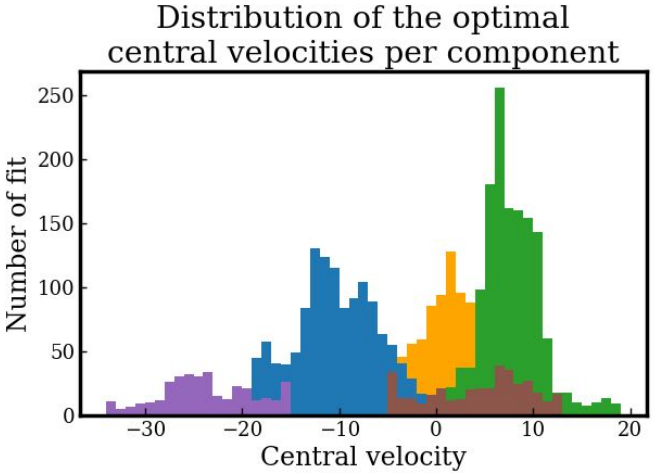
For each stacked line we:

- remove a random number of transition from the stack
- (try to) fit 5 Voigt profiles to the data
- repeat ×100

All CRRLs lines detected (after stacking) towards Tau A (100h observing time), *Cros et al (in prep)*

CRRLs: components separation



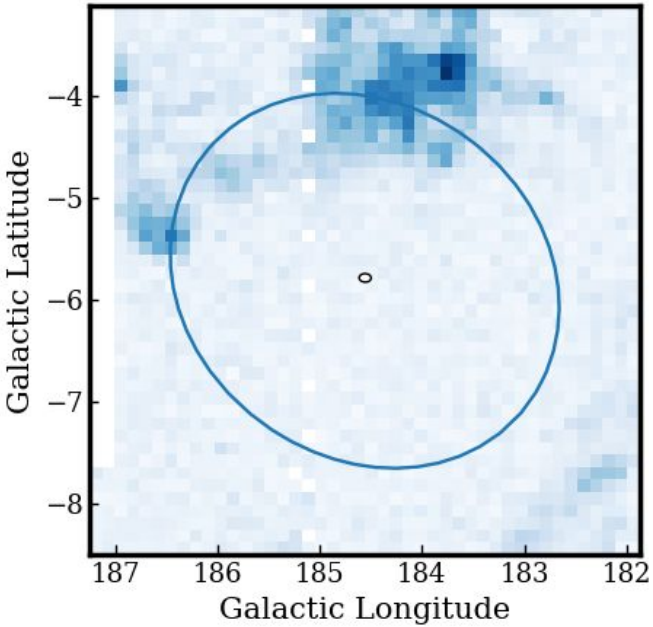


3 components arise:

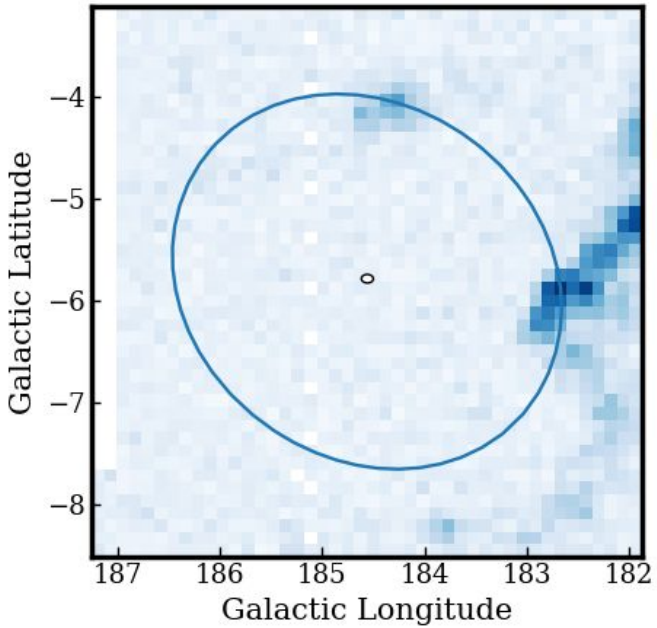
7 km/s, 2 km/s, -10 km/s

CO and HI HI only

Spatial identification: CO



3 km/s



7 km/s

Perspectives

- Spatially separate the HI velocity components using Gaussian decomposition
- Carry-out observations towards clouds identified in CO and HI
- Using another tracer (synchrotron) to constraint T_0
- Extract physical parameters for the detected components
- And of course: apply to other sources !

Thanks for listening !